“Local Universe” (within ~ 20 Mpc) Distance Indicators

if we know the absolute magnitude of an object (M) and can measure its apparent magnitude (m), we can derive the distance from

$$m - M = 5\log d - 5$$

(where remember the distance must be expressed in parsecs!)

Propagation of errors show how the uncertainty in distance relates to the uncertainty in distance modulus:

$$\frac{\sigma_d}{d} \approx 0.5 \times \sigma_{(m-M)}$$

Local Universe Standard (or Standardizable) Candles:

- Pulsating Variables: Cepheids or RR Lyrae stars *(already talked about)*
- Tip of the Red Giant Branch (TRGB)
- Surface Brightness Fluctuations (SBF)
- Planetary Nebulae Luminosity Function (PNLF)
- Globular Cluster Luminosity Function (GCLF)

Tip of the Red Giant Branch

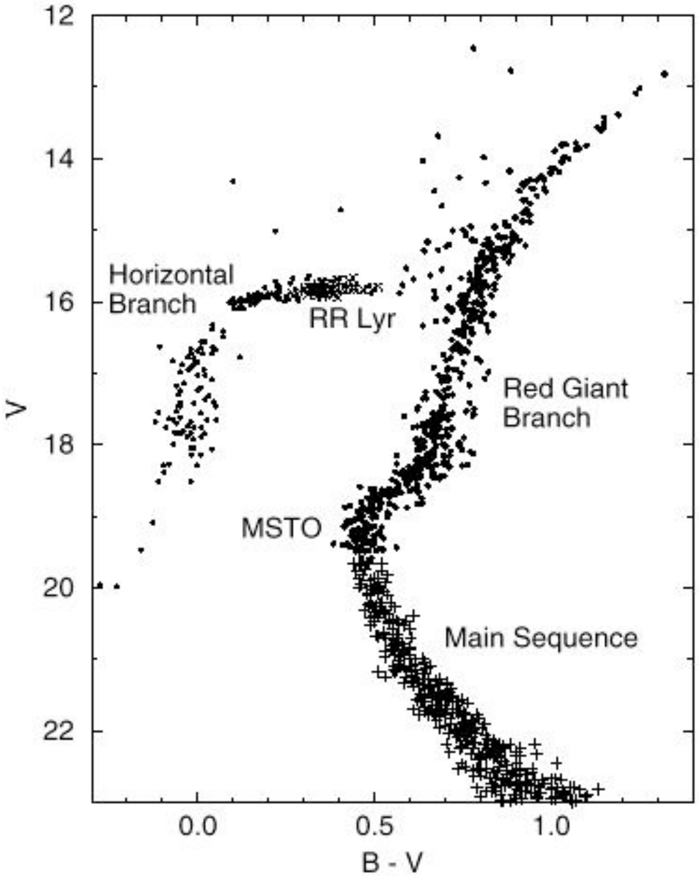
Consider the evolution of stars like the Sun.

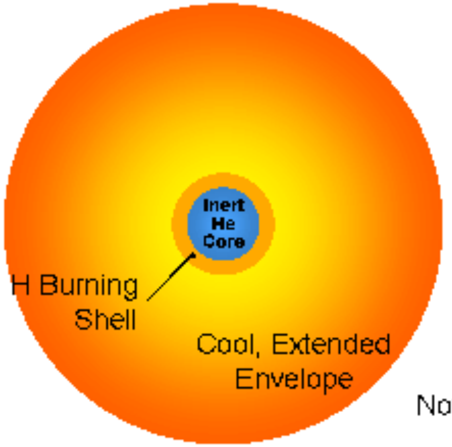
After they exhaust hydrogen in the core, they evolve off the main sequence.

The helium core contracts and heats up; hydrogen burning happens in a shell around the core at a furious pace. The star becomes luminous and swells up, becoming a red giant.

When the core contracts and heats enough to begin fusing helium into carbon and oxygen, that energy release expands the core, reducing the nuclear reaction rates and causing the star to evolve off the RGB and onto the horizontal branch.

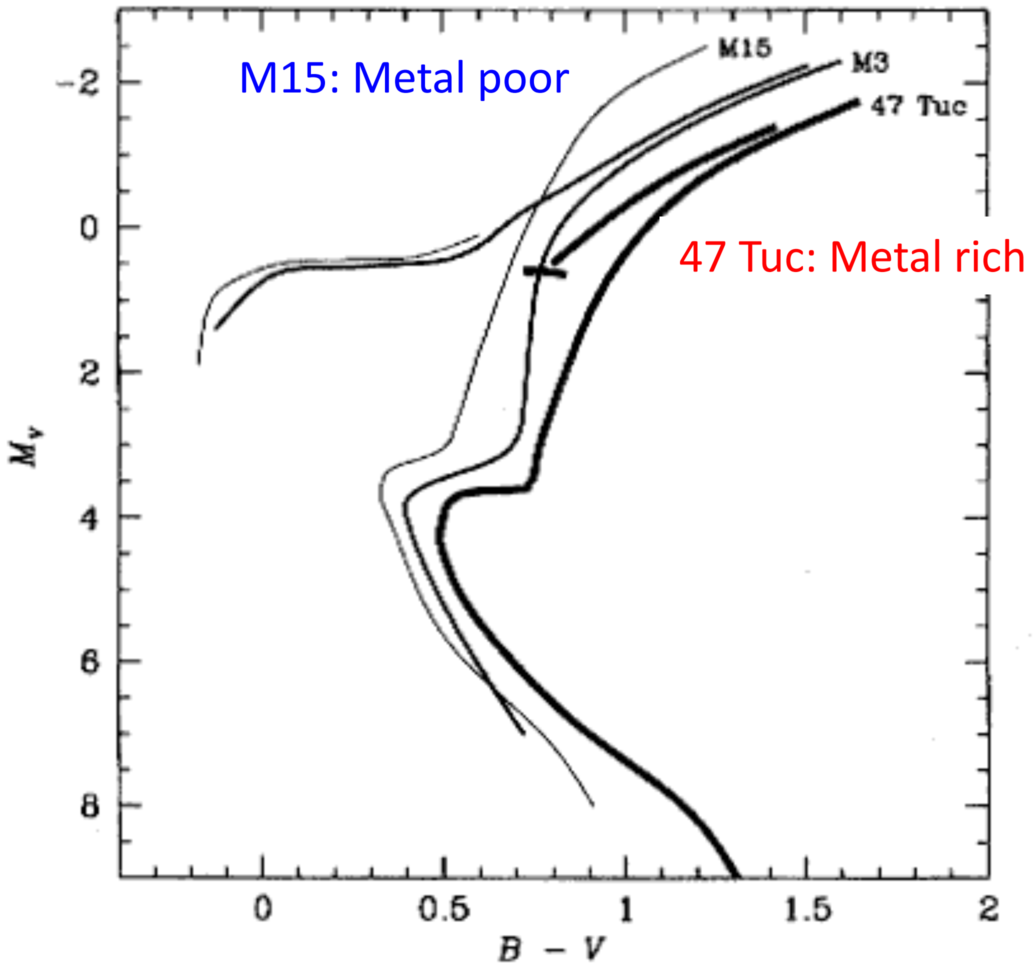
The RGB “Tip” is the brightest luminosity a RGB star can attain in its evolution. If a galaxy is close enough for us to see individual stars, we can use TRGB to get a distance.





Not to Scale

Red Giant Branch Metallicity Effects



M15: Metal poor

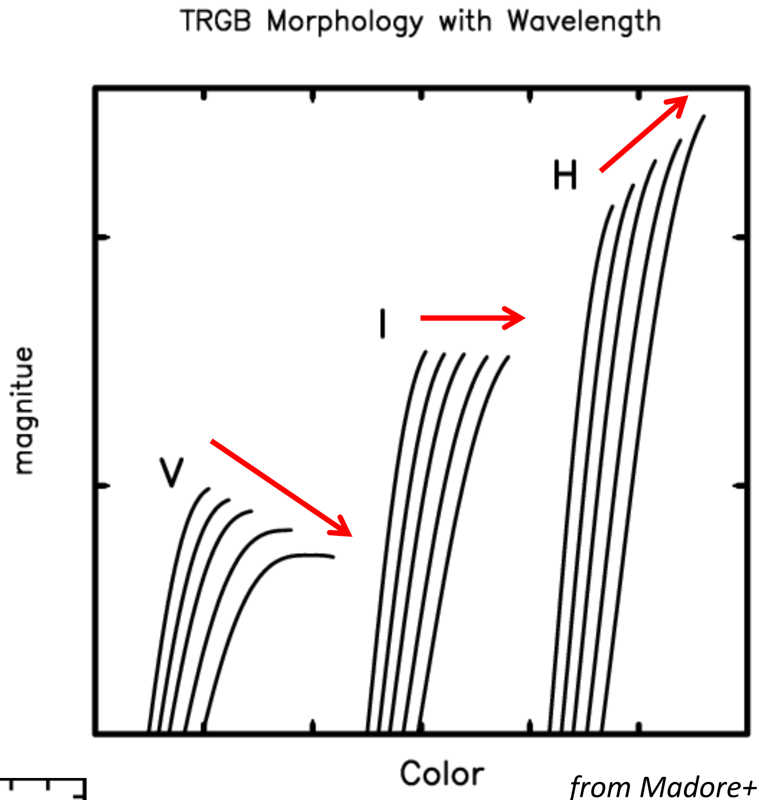
47 Tuc: Metal rich

Figure 6.3 Schematic illustration of the principal sequences in the CM diagrams for three globular clusters. The systems shown are a metal-rich cluster (47 Tuc), an intermediate-metallicity cluster (M3), and a metal-poor cluster (M15). [Sequences from Hesser *et al.* (1987) and Buonanno *et al.* (1994)]

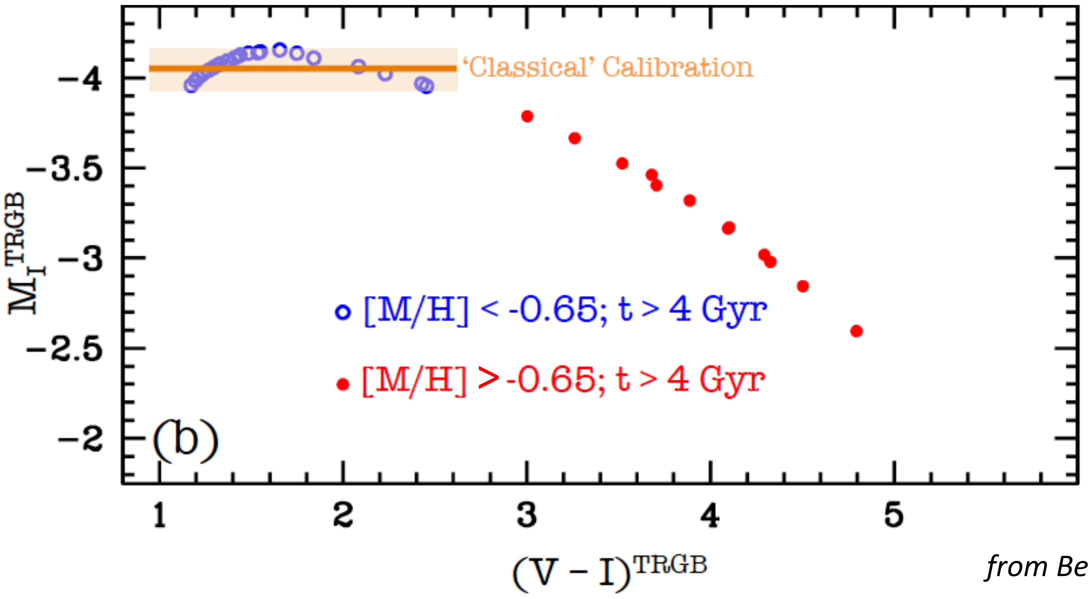
Calibrating the Tip

We need to know the absolute magnitude of the TRGB. But this is ***metallicity-dependent***: metal-rich RGB stars are redder, and so their flux moves into redder filters.

As a function of metallicity, the RGB tip becomes fainter in optical filters, brighter in infrared filters.



from Madore+18



from Beaton+18

We can calibrate the RGB tip using stellar evolution models. Works best for old populations.

Measuring the Tip

NGC 185

from Beaton+18

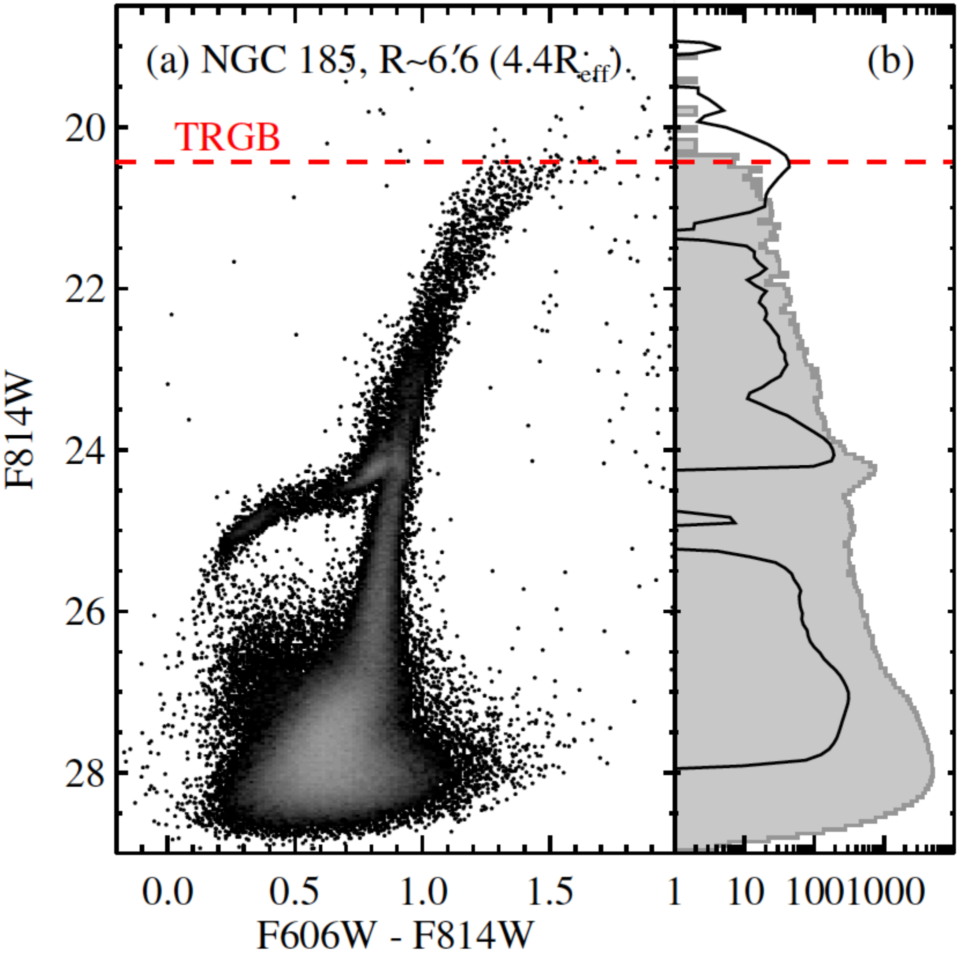


Fig. 29 Demonstration of the TRGB measurement process for the Local Group galaxy NGC 185 using *HST*+ACS data. (a) F814W - (F606W-F814W) CMD of resolved stars in its outer region ($R > 4.4R_{eff}$). The TRGB is marked by a dashed line. (b) F814W-band luminosity function of resolved stars (histogram) and corresponding edge-detection response (solid line). A strong edge-detection response is seen at the TRGB ($F814W_{TRGB} = 20.43 \pm 0.03$ mag).

Measure RGB color and tip magnitude

- RGB color → $M_{tip} = -4.06 \pm 0.12$
- $m_{tip} = 20.43 \pm 0.03$

$m-M = 20.43 - -4.06 = 24.49$

then correct for 0.28 mag of extinction to get:

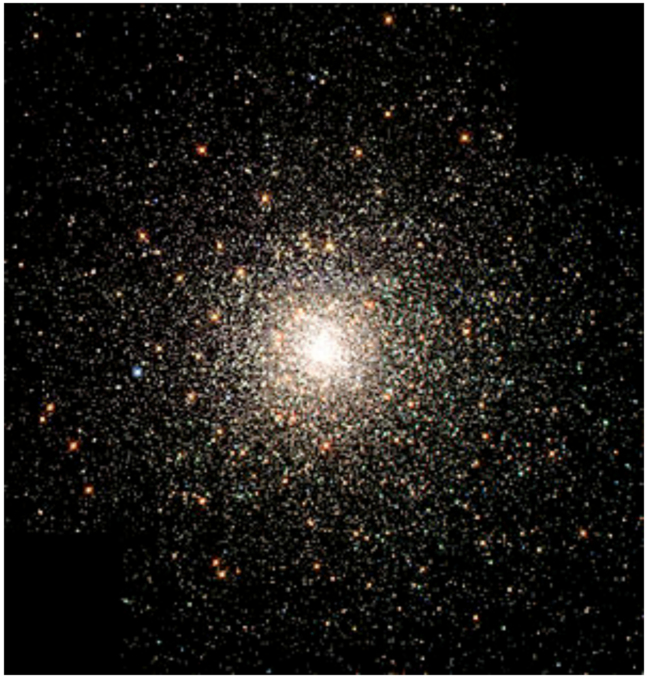
$m-M = 24.21 \pm 0.03$ (ran) ± 0.12 (sys)

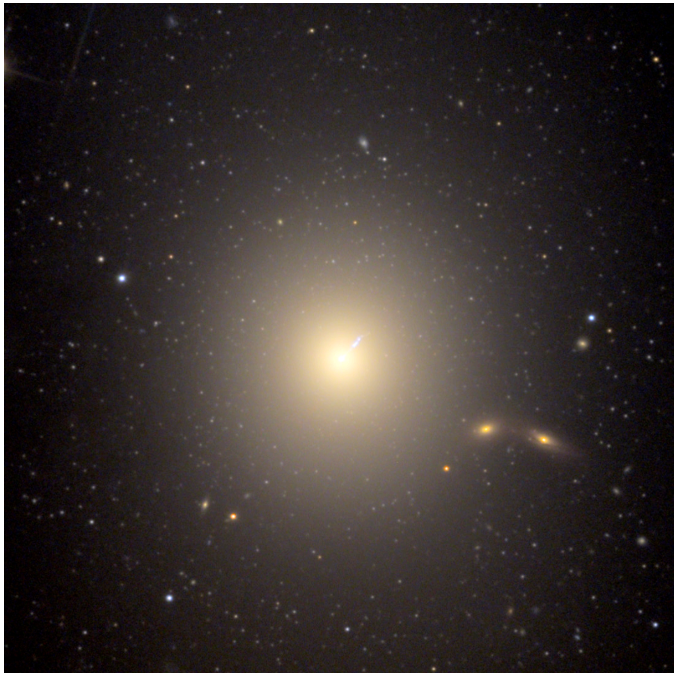
or d = 0.7 ± 0.08 Mpc

Current distance limit ~ Virgo (16.5 Mpc)

Surface Brightness Fluctuations

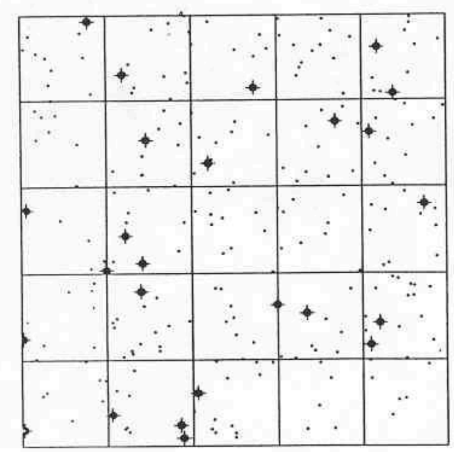
Think of a globular cluster versus an elliptical galaxy. Which looks "grainier"?



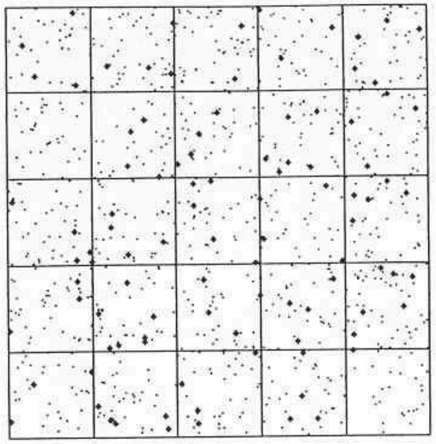


SBF method

Think of taking an image of two galaxies at different distances.



Nearby galaxy



Distant galaxy

Number of stars per pixel: $\frac{N_*}{\mathrm{pix}} \sim d^2$

Flux from the individual stars: $f_* \sim d^{-2}$

So the surface brightness doesn't change: $\mathrm{SB} \sim N_* \times f_* = \mathrm{constant}$

But in a given image, the random scatter in pixel intensities goes as $\sigma_I \sim \sqrt{N_*} \times f_* \sim d^{-1}$

So consider the pixel variance divided by average surface brightness:

$$\frac{\sigma_I^2}{\mathrm{SB}} \sim \frac{N_* f_*^2}{N_* f_*} \sim f_*$$

where f_* can be related to (but is not the same as!) the average flux per star. Expressed in magnitudes, this is referred to as the *fluctuation magnitude*.

Same metallicity effect that we saw using TRGB stars.

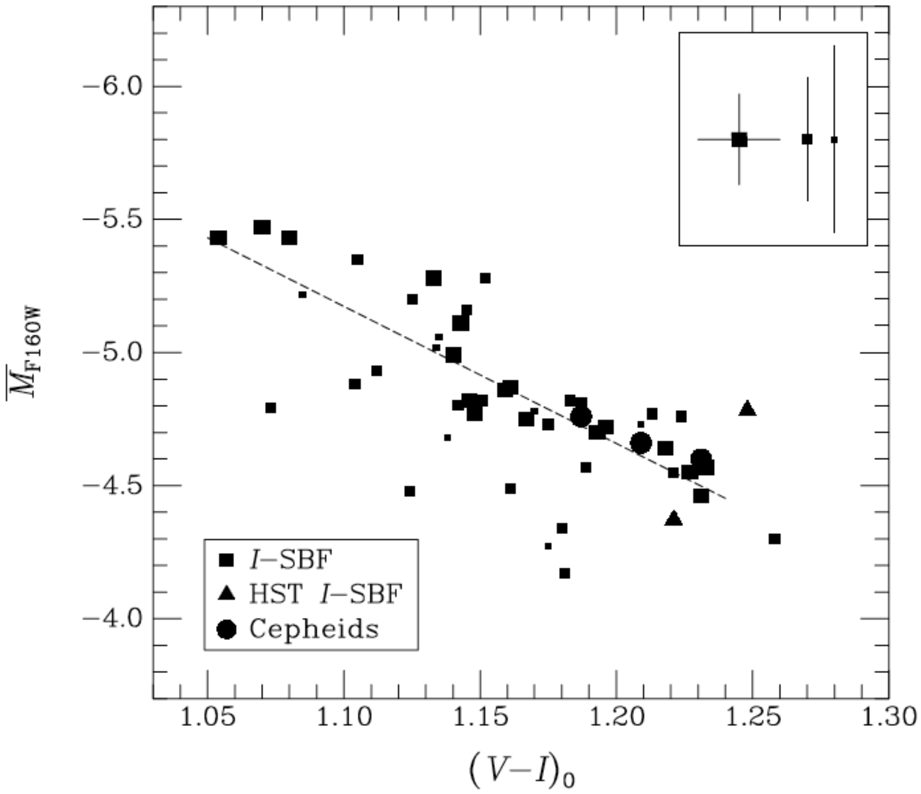


FIG. 1.—Absolute fluctuation magnitudes $\overline{M}_{\rm F160W}$ vs. the extinction-corrected $(V-I)_0$ color for the 47 galaxies that show no signs of dust in the Camera 2 field of view. The square points represent $\overline{M}_{\rm F160W}$ values derived using ground-based *I*-band SBF distances, and the triangles indicate galaxies with *I*-band SBF distances measured with WFPC2 on *HST*. The size of each point indicates the uncertainty in $\overline{M}_{\rm F160W}$. The largest points have uncertainties less than 0.2 mag, the medium-sized points fall between 0.2 and 0.3 mag, and the smallest points have uncertainties greater than 0.3 mag. Median error bars for each point size are shown at the top of the figure. The circles indicate three galaxies with reliable Cepheid distances (NGC 224 = M31, NGC 3031 = M81, and NGC 4725). They are also plotted using their *I*-band SBF distances.

Jensen+ 03

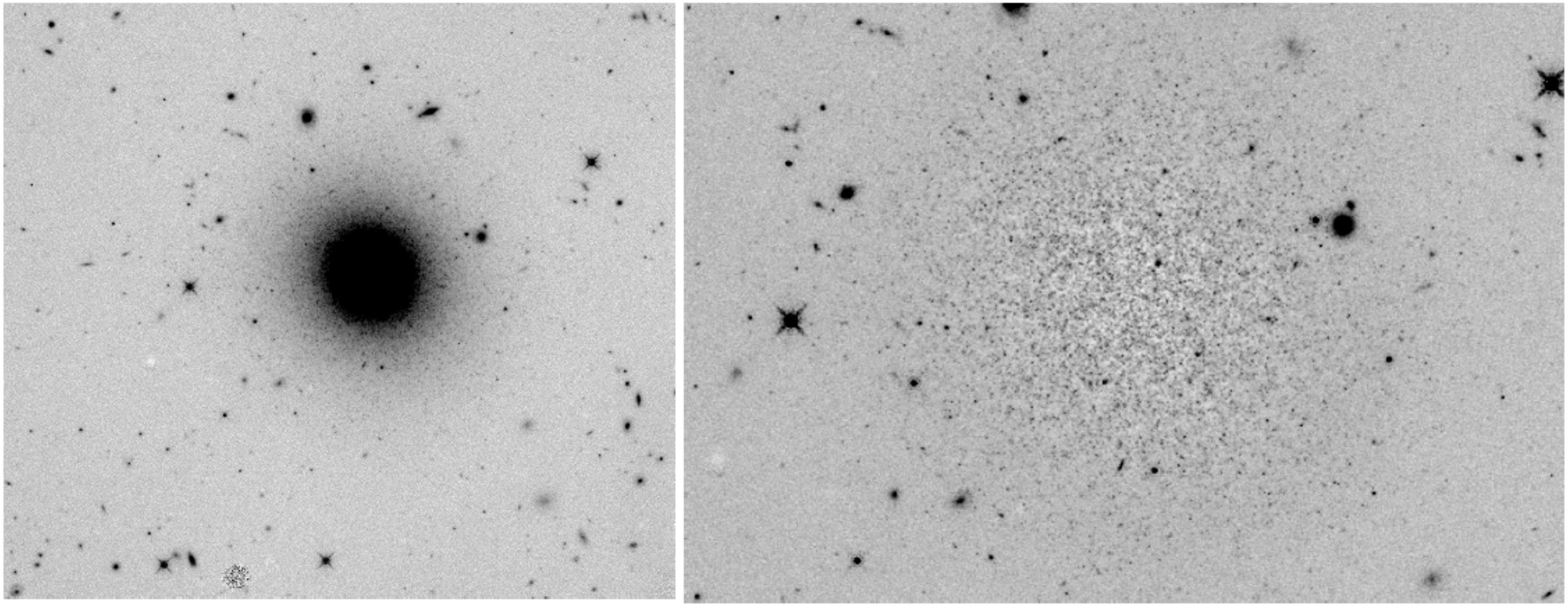
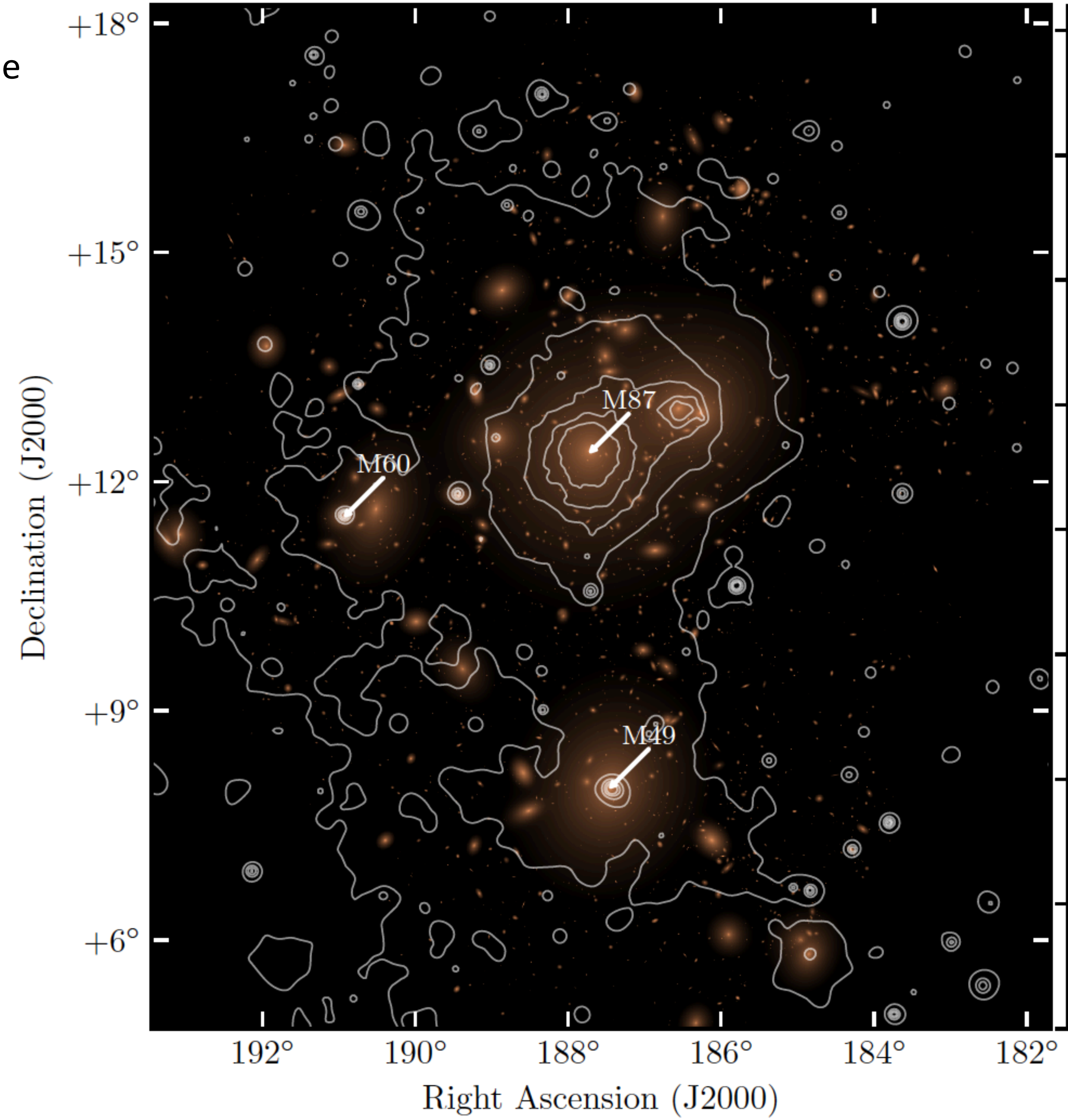


Fig. 7 WFC3/IR image of the Virgo galaxy IC 3032 in the F160W bandpass (left); an enlarged view of the image after galaxy model subtraction (right). The fluctuations are evident.

What kind of galaxy would this work well for? What kind wouldn’t it work well for?

SBF distance application: the structure of the Virgo Cluster

(map courtesy Spengler+18)



Virgo cluster “tomography”:

Virgo elliptical galaxies at different distances (Mei+07)

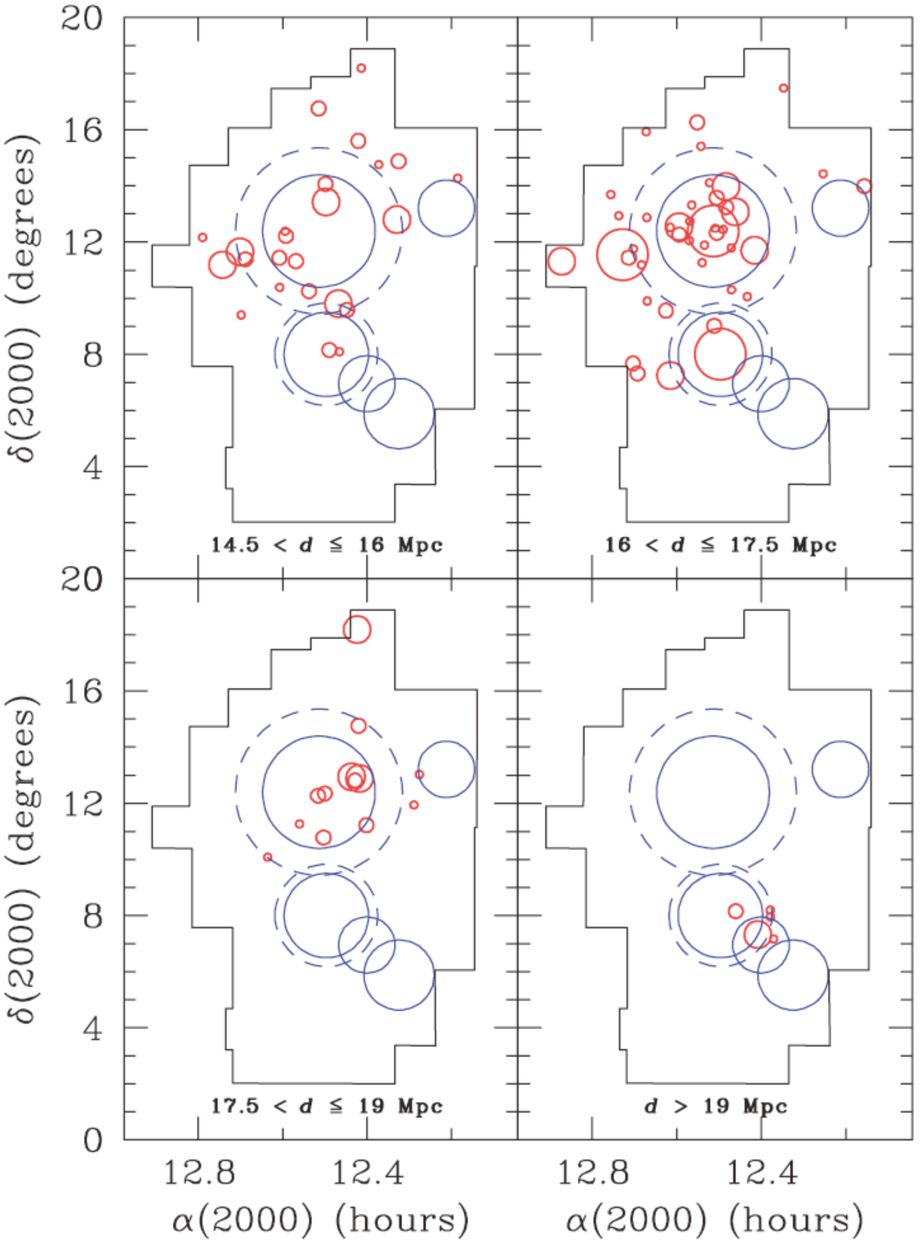
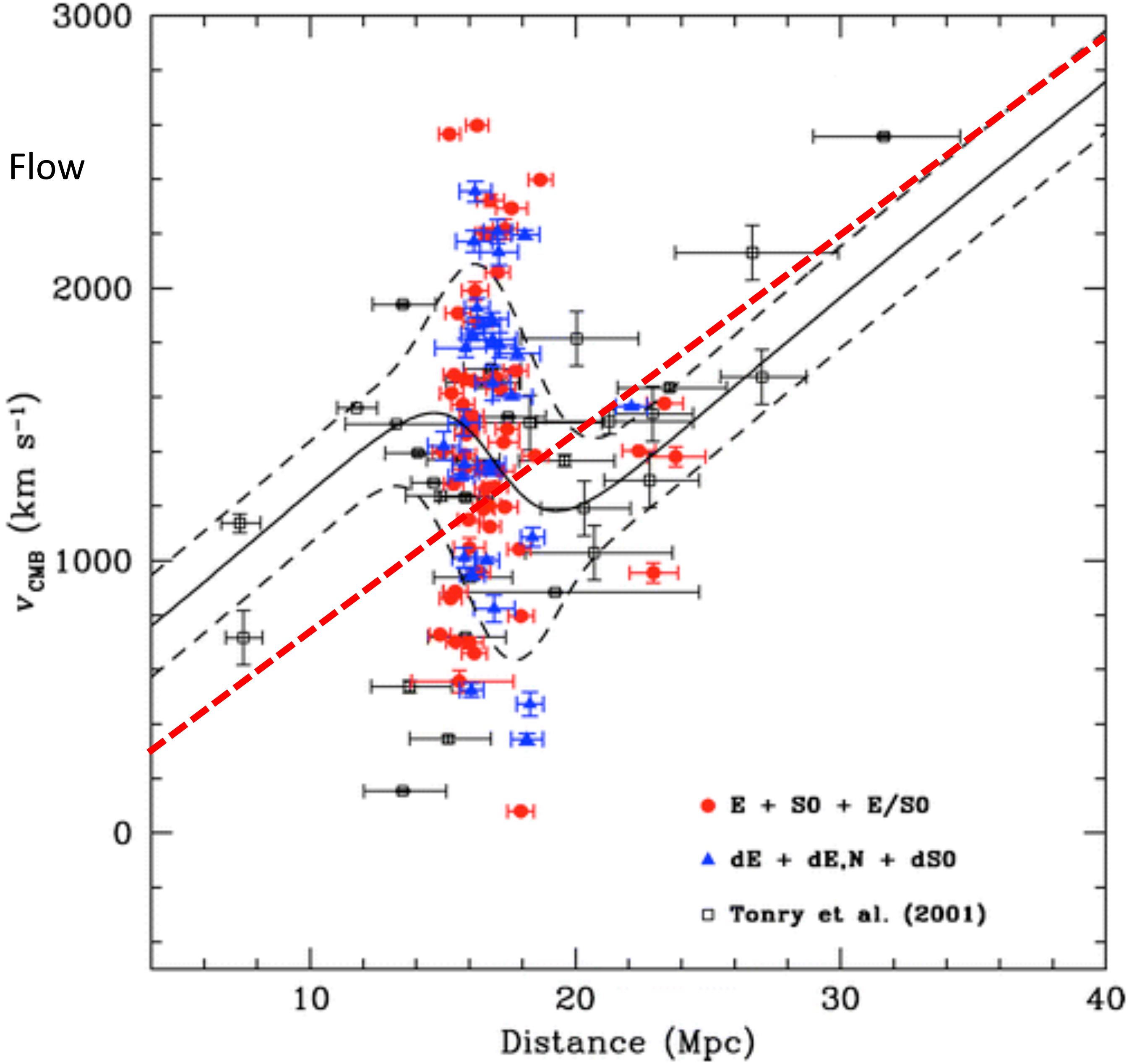


FIG. 7.—Distribution on the sky of 84 galaxies from the ACSVCS (*red circles*) with measured SBF distances, displayed in four ranges in distance: $14.5 < d \leq 16$ Mpc (*top left*); $16 < d \leq 17.5$ Mpc (*top right*); $17.5 < d \leq 19$ Mpc (*bottom left*); and $d > 19$ Mpc (*bottom right*).

Virgo velocity field:

distortion of the Hubble Flow (Mei+07)



Planetary Nebula Luminosity Function

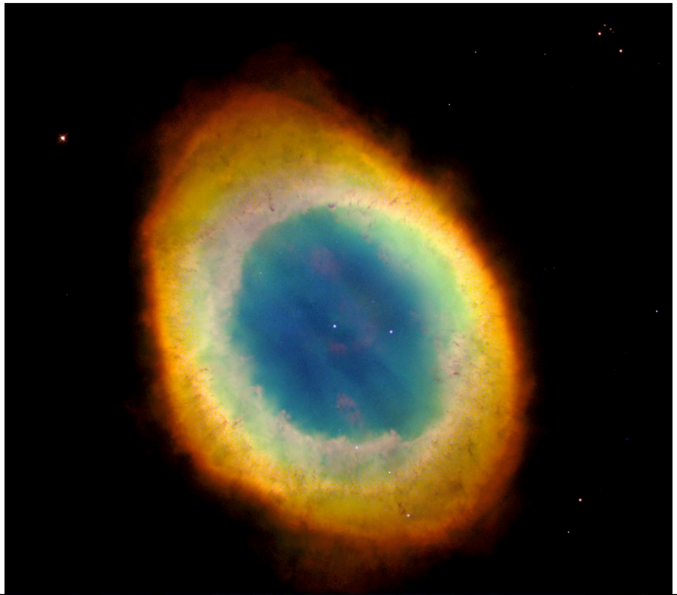
Stellar evolution recap:

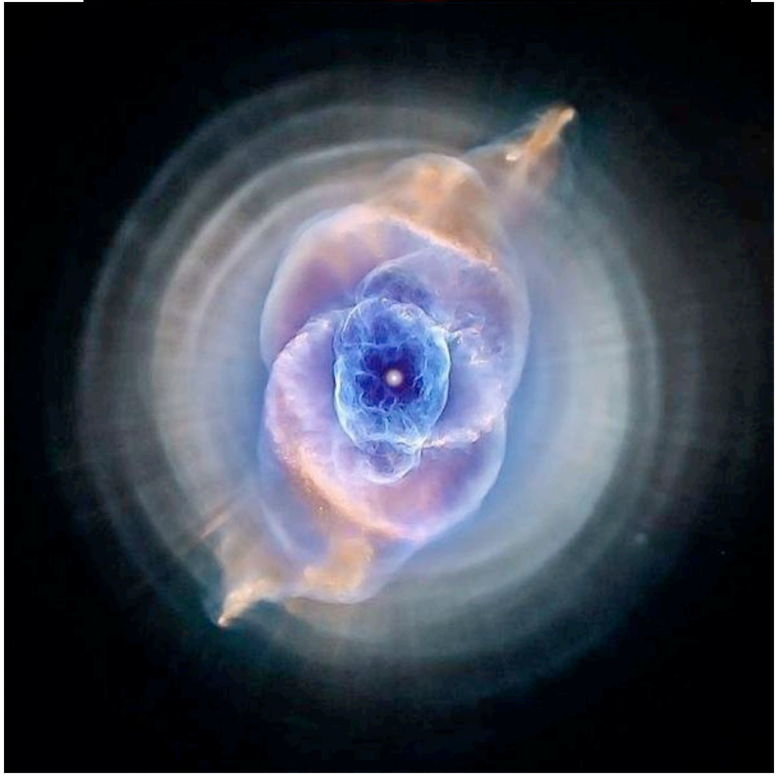
At the end of their lives, after they run out of He in their core, solar type stars eject outer layers.

The hot C/O core (young white dwarf) ionizes these expanding shells, causing them to fluoresce.

We see them in optical emission lines (most notably [OIII]5007A).

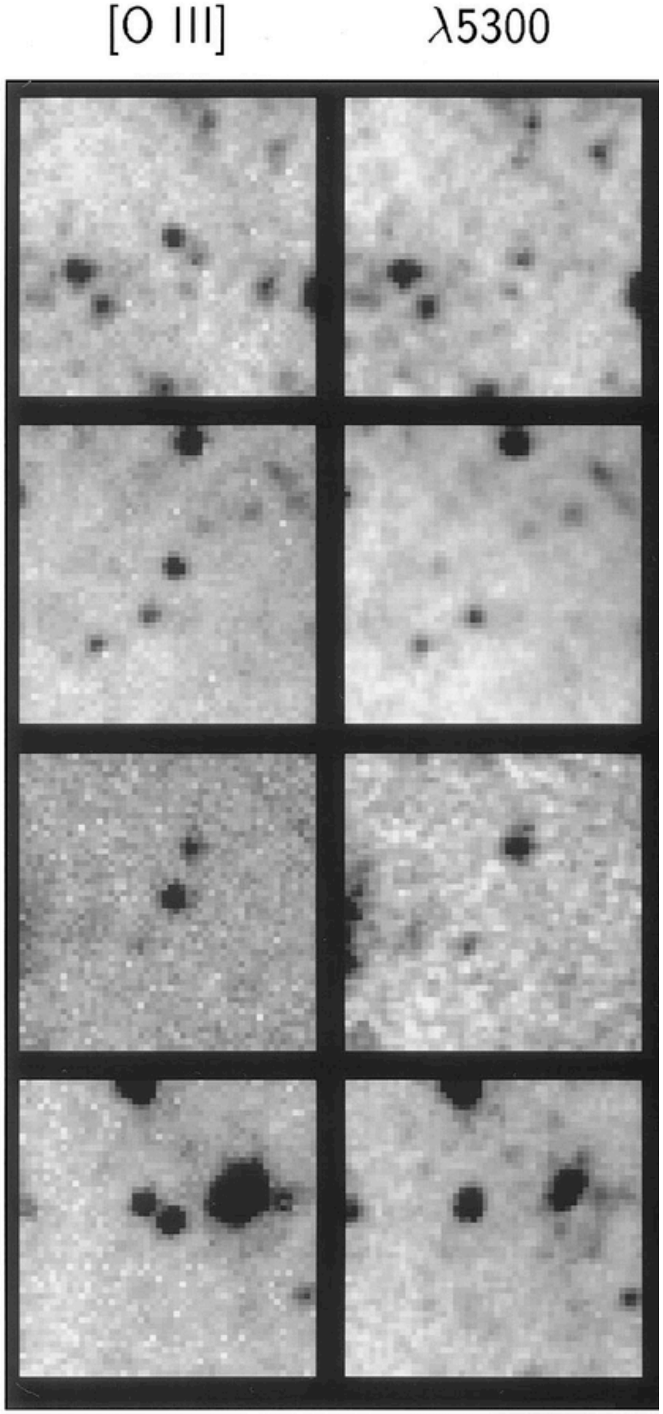
Beautiful in our galaxy, but small (parsec scale). In other galaxies they are simply unresolved emission line sources.



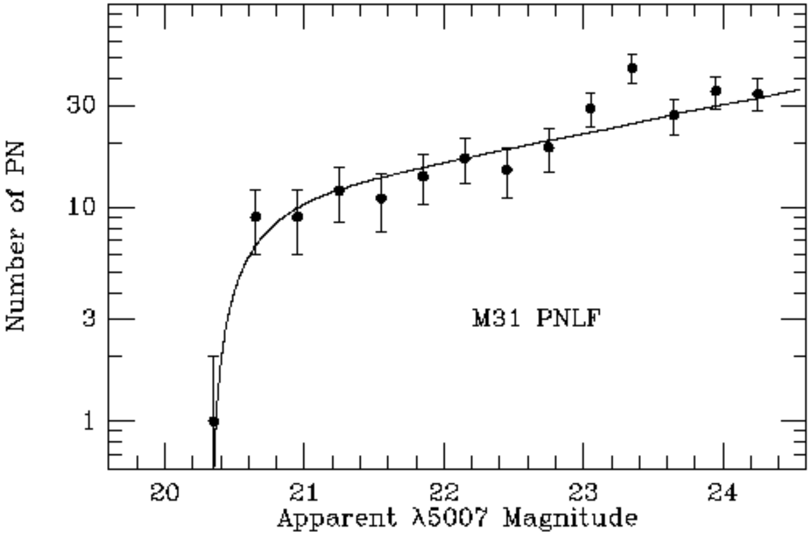


Pne in M101 (Feldmeier+ 09)

[OIII]: emission line
5300: continuum (regular starlight)



Planetary Nebula Luminosity Function

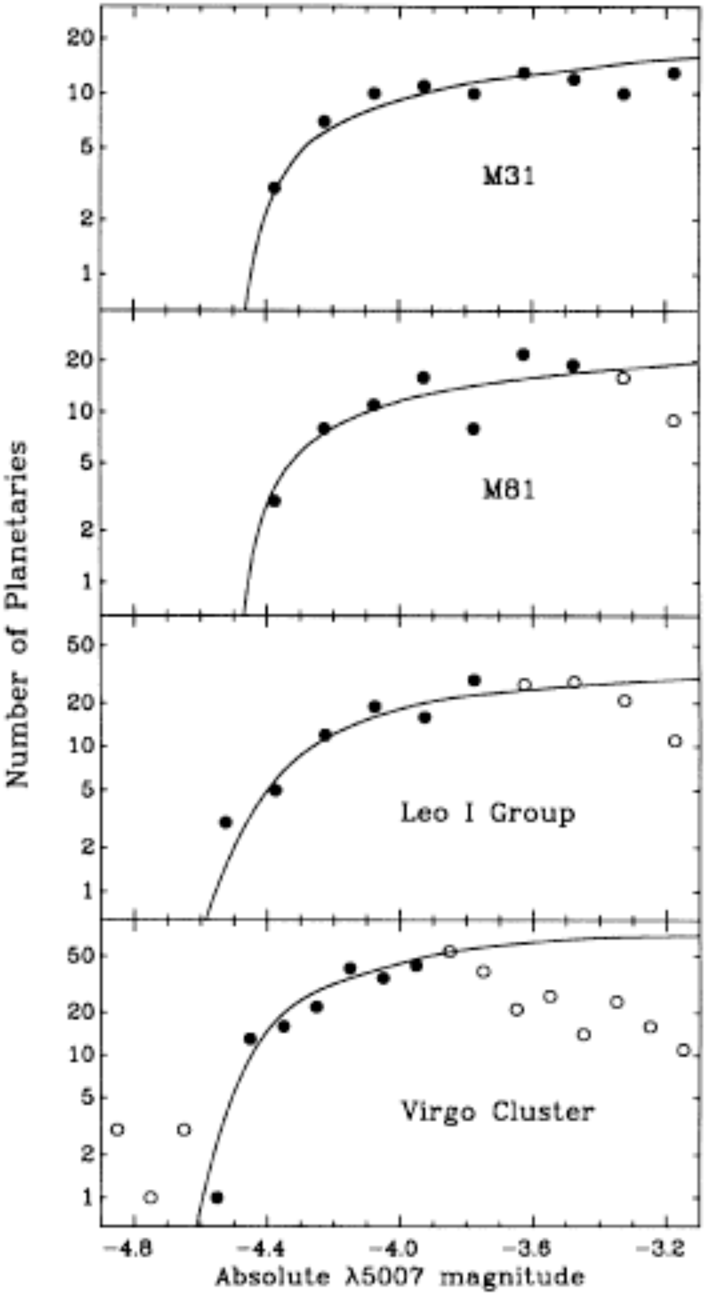


PNLF: Number of PNe as a function of emission line luminosity.

The PNLF shows a sharp cutoff at bright magnitudes, related to the maximum size of the ionizing WD.

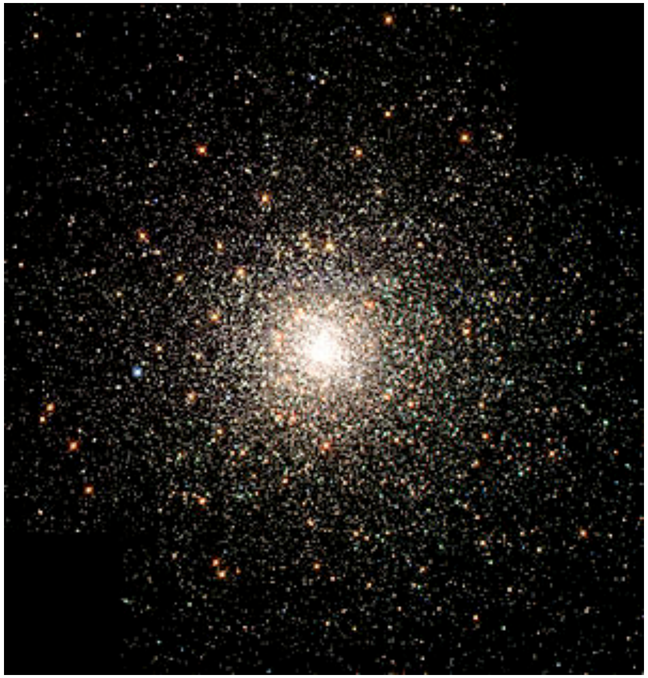
$$N(m) \sim e^{0.307M}(1 - e^{3(M^*-M)})$$

M* = −4.53 ± 0.06 (Ciardullo+12)



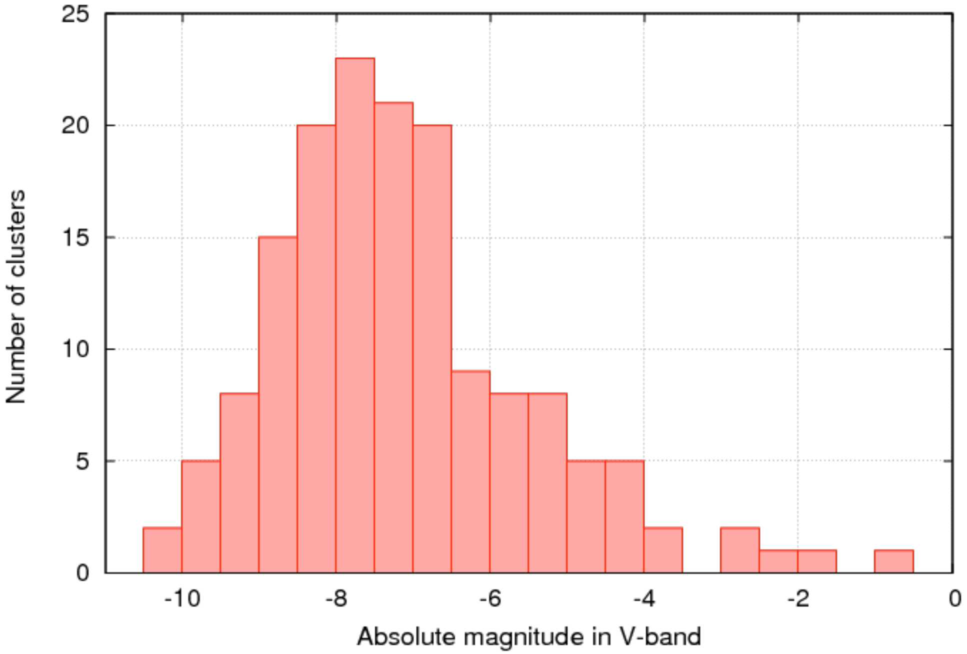
Globular Cluster Luminosity Function

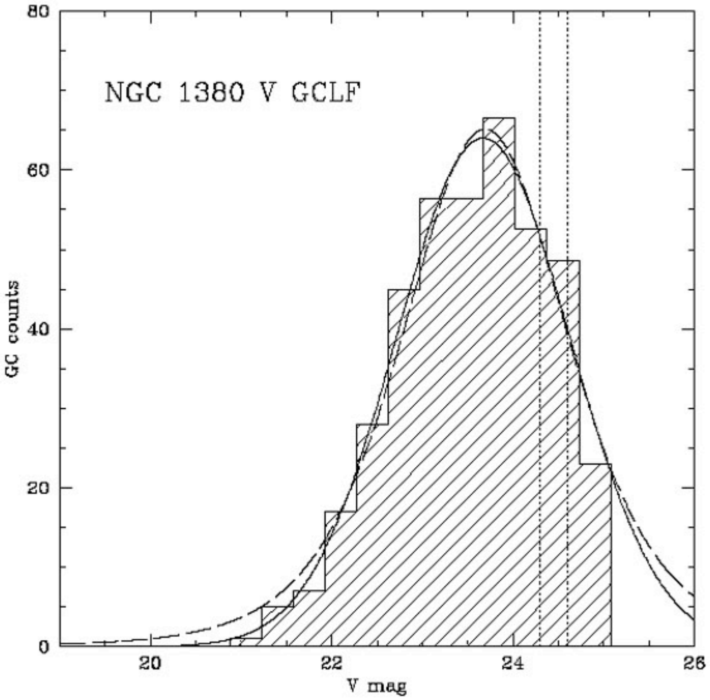
GC (M80) in the Milky Way



GCs in the Virgo Cluster (little dots)

Globular Cluster Luminosity Function

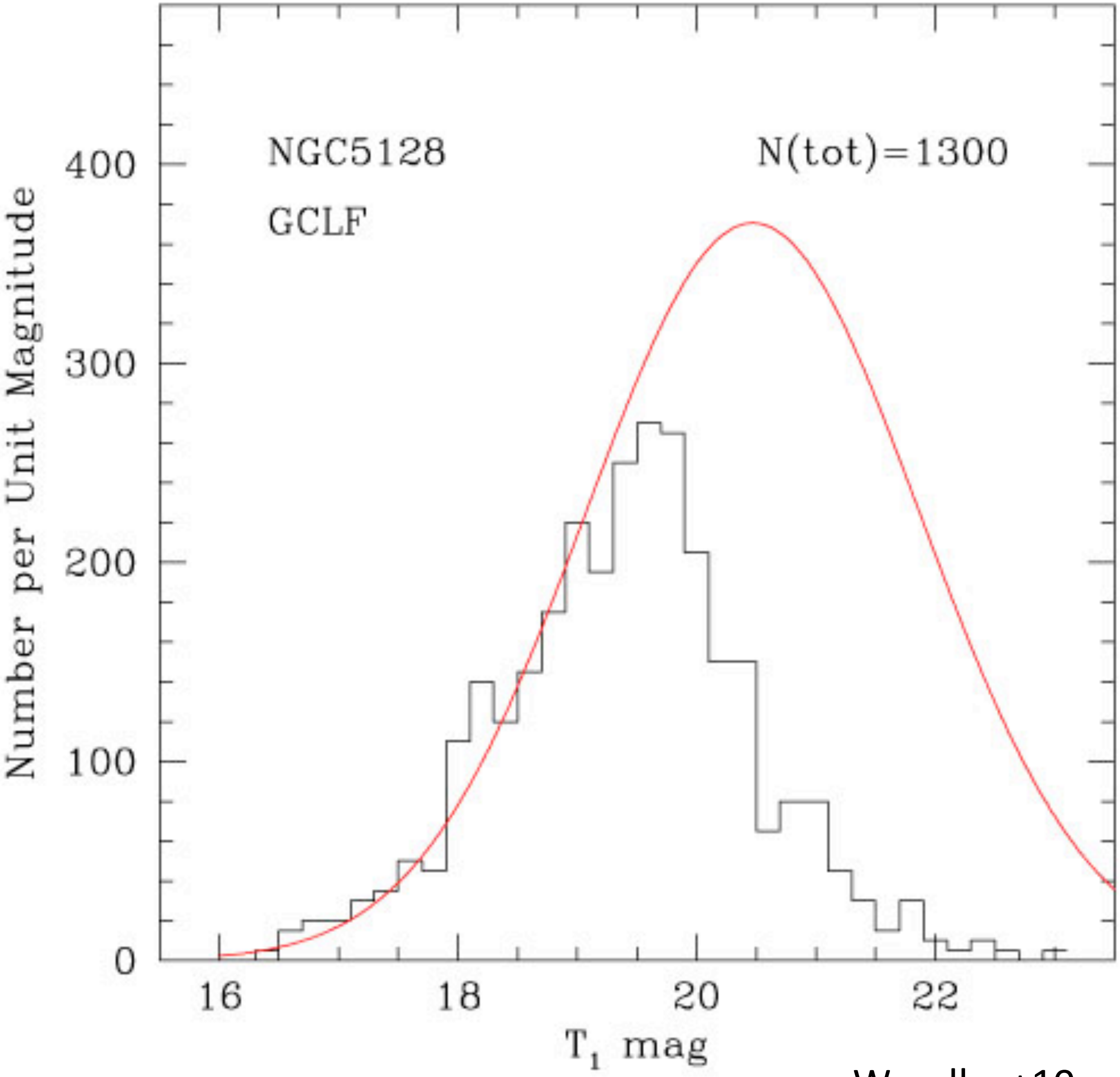

Globular Clusters in the Milky Way (Harris 2010 catalog)



GCLF typically modeled as a Gaussian. If the magnitude of the peak (note: not the same as the peak magnitude!) is constant across galaxies, this can be used as a distance indicator.

While GCs can be bright, you need to see the faint ones to estimate the peak!

Observational incompleteness at faint magnitudes is a real complication.



Woodley+10

Comparison of local distance indicators

M101, the Sombrero Galaxy
(McQuinn+16)